

Pre-Explosive Observational Properties of Type Ia Supernovae

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ABSTRACT

The evolutionary path of rotating CO White Dwarfs directly accreting CO-rich matter is followed up to few seconds before the explosive breakout in the framework of the Double Degenerate rotationally-driven accretion scenario. We compute several models with different initial masses and physical conditions, following all the evolutionary phases, from the heating process during the pre-merging phase, through the two self-regulated accretion phases, up to the final central C-ignition and the development of an extended convective core.

We find that the evolutionary properties (both structural and observational) depend only on the actual mass of the accreting White Dwarf and not on the previous history. We determine the expected frequency and amplitude of the gravitational wave emission, which occurs during the mass transfer process and, as a matter of fact, acts as a self-tuning mechanism of the accretion process itself. The gravitational signal related to Galactic sources can be easily detected with the next generation of space-born interferometers and can provide notable constraints to the progenitor model. The expected statistical distribution of pre-explosive objects in the Galaxy is provided also in the effective temperature-apparent bolometric magnitude diagrams which can be used to identify merged DD systems via UV surveys, once the contribution of the accretion disk is properly taken into account.

We emphasize that the thermonuclear explosion occurs owing to the decay of physical conditions keeping over-stable the structure above the classical Chandrasekhar limit and not by a steady increase of the WD mass up to this limit. This conclusion is independent of the evolutionary scenario for the progenitors, but it is a direct consequence of the stabilizing effect of rotation. Such an occurrence represents an epistemological change of the perspective in defining the ignition process for accreting WDs. Moreover, this requires a long evolutionary period (of at least several million years) to attain the explosion after the above mentioned conditions cease to keep stable the WD. Therefore it is practically impossible to detect the trace of the exploding WD companion in recent pre-explosion frames of even very near SN Ia events.

Key words: stars: binaries: close – stars: rotation – stars: supernovae: general – gravitational waves.

1 INTRODUCTION

The recent discovery of the type Ia Supernova (SN Ia) SN2011fe in the nearby galaxy M101 has reawakened the interest to get direct information on the progenitor systems of these explosive events, searching in archive images any signature to distinguish among various progenitor models (see, *e.g.*, Bloom et al. 2012). In principle, once

the scenario for the progenitors has been fixed, the evolutionary path up to the explosion can be modeled and the results compared with the observational data obtained before explosion. **In recent years, this approach has been adopted by many authors, even if no definite conclusions on the nature of SNe Ia progenitors has been obtained (see Maoz & Mannucci 2008; Voss & Nelemans 2008; Nielsen, Voss & Nelemans 2012; Li et al. 2011b).**

Both the two most common scenarios for type Ia SNe progenitors, the Double Degenerate (DD) and the

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Single Degenerate (SD) scenarios, require that rotation plays an important role in the evolution of accreting WDs (Piersanti et al. 2003b - hereinafter PGIT, Di Stefano et al. 2011, Hachisu et al. 2012). This is true also for the Core Degenerate scenario by Kashi & Soker (2011), assuming that a CO WD merges with the core of AGB star soon after the end of a Common Envelope phase. In this case an evolutionary time lasting more than 10^6 yrs is expected from the halting of the accretion process up to C-ignition in highly degenerate physical conditions and, after an additional short time related to the simmering phase, to the explosion. This implies, as will be discussed later on, that it is not possible to find in archival images any hints about the typology of the donor star, but it will be possible to observe only the exploding star, whose properties are almost independent of the considered scenario for the progenitors. As a matter of fact the only possibility to derive information about the mass transferring companion (that is the progenitor model) is to detect observationally some features characterizing the evolving system during the mass accretion phase and beyond, up to the explosion.

In the present work we focus our attention on the Double Degenerate scenario, assuming that SNe Ia arise from binary systems made by two CO White Dwarfs (WDs) with total initial mass larger than the canonical Chandrasekhar mass limit M_{Ch} and with an initial orbital separation small enough to allow the merging of the two components via gravitational wave radiation (GWR) on a timescale smaller than the Hubble time (Iben & Tutukov 1984; Webbink 1984). According to Benz et al. (1990) and Rasio & Shapiro (1995) the less massive component overfills its own Roche lobe and completely disrupts. The debris of this WD forms an accretion disk from which matter flows to the more massive survived companion (Tutukov & Yungelson 1979).

One first shortcoming for this scenario is the conjecture that during the merging process carbon could be ignited near the surface of the accreting star and the burning transferred very rapidly towards the inner regions, thus producing as a penultimate outcome a O-Ne-Mg WD. The latter will eventually collapse into a neutron star (Isern et al. 1983; Hernanz et al. 1988), producing an explosive event, but not a thermonuclear Supernova. This has been excluded by Lorén-Aguilar, Isern & García-Berro (2009), who find that early C-burning indeed occurs, but it is soon extinguished.

The second important shortcoming is that, after the merging, the mass transfer from the disk to the surviving WD occurs at a very high rate, close to the Eddington limit ($\dot{M}_{\text{Edd}} \sim 10^{-5} M_{\odot} \text{yr}^{-1}$), so that off center C-burning has to occur at the base of the accreted layers well before the WD could attain M_{Ch} (Saio & Nomoto 1985, 1998).

However, PGIT have shown that, if the effects of rotation, which naturally arise in merging DD systems, are taken into account, the accretion process becomes “self-regulated”, producing, at the end, a degenerate central carbon ignition and a type Ia SN-like outburst. Another important result of the rotating Double Degenerate scenario is that the total mass of the accreting WD can increase above the canonical M_{Ch} , up to the corresponding mass limit for rotating degenerate objects. If for the accreting WD very high efficiency of angular momentum transport is assumed (rigid body rotation) as in PGIT, such a limit is $\sim 1.5M_{\odot}$, but

it could be larger, up to $\sim 4M_{\odot}$, for differentially rotating objects, depending on the angular momentum distribution (Ostriker & Bodenheimer 1968). However, it has to be noted that the maximum total mass of binary CO WDs systems is limited in nature to $\sim 2.2 - 2.4 M_{\odot}$ due to evolutionary constraints.

As first suggested by Piersanti et al. (2009), the accreting CO WD will naturally evolve to the explosion, once it has accreted over the classical M_{Ch} in an over-stable condition, independently of the assumed efficiency of the angular momentum transport in the accreting structure, either because angular momentum is lost from the star by viscous friction (rigid rotating body) or because angular momentum is redistributed through the structure via viscous shear (differentially rotating body).

We remark that rotation, besides acting as the leading parameter of the accretion process, implies also a deep change of perspective in our understanding the evolution up to the explosion. In fact we are no longer faced with a matter-accreting WD simply growing to a mass limit and, hence, experiencing a strong compression which triggers the explosion. By contrast, we face with an over-stable rotating structure still increasing in mass also after the mass limit has been largely exceeded, because the actual total mass remains smaller than the *rotating* M_{Ch} . Such an occurrence may allow all the mass available in the binary system to be accreted onto the WD. Later on, owing to either the loss or the redistribution of angular momentum, the value of the rotating M_{Ch} decreases and only when it approaches the actual total mass of the WD, the whole structure strongly contracts, producing the central degenerate C-ignition. Such a process reminds of what occurs in the degenerate cores of massive stars at the onset of the collapse, when, owing to deleptonization, M_{Ch} decreases below the actual value of the core itself and not vice-versa.

The evolutionary scenario proposed by PGIT provides a detailed description of the physical properties of the accreting WD from the merging phase up to the Supernova explosion, thus allowing the definition of observable quantities which can be used to put more firm constraints on the SN progenitor systems. A similar approach, but employing an even earlier evolutionary phase, has been followed recently by Badenes & Maoz (2012).

In §2 we review the scenario for the merging of two CO WDs and we address the problem of the long term evolution of the merged object. We also review the input physics and the numerical procedures adopted to compute evolutionary sequence of accreting WDs according to the PGIT prescriptions. The assumptions and their implications are also discussed. In §3 we discuss the surface observable properties of accreting WDs during the whole process, from the merging up to the Supernova explosion. This has been done for various original masses of the accreting White Dwarf. According to the obtained results we identify some key evolutionary properties of accreting WDs and we demonstrate that they are independent on the initial physical conditions of the post-merging object. We define also the properties of the gravitational signal related to the self-regulated accretion phase. In §4 we determine for the Galaxy the expected number objects experiencing the various accretion phases and we also define

the expected signals, both in the electromagnetic and in the gravitational wave radiation domain. In our analysis we ignore all those systems with a total mass too small to provide an explosive outcome (“SN manque” systems), focusing our attention only on DD systems good candidates as SNe Ia progenitors. Our conclusions are summarized in §5.

2 MERGING WDS: AN OVERVIEW

The merging process of two White Dwarfs has been discussed by many authors during the last three decades, even if it has not been attained so far a firm and widely accepted conclusion on the outcomes.

After the pioneering works by Benz et al. (1990) and Rasio & Shapiro (1995), a re-analysis of the merging phase of two CO WDs has been performed using SPH simulations by Guerrero et al. (2004), Rosswog (2007), and Lorén-Aguilar, Isern & García-Berro (2009). The obtained results confirm that the less massive component completely destroys in a dynamical timescale, forming an hot and thick accretion disk around the surviving companion. The timescale on which the merging occurs has been the subject of several discussions (see, e.g., D’Souza et al. (2006) and Motl et al. (2007) Dan et al. (2011) Isern, García-Berro & Loren-Aguilar (2012) Raskin et al. (2012)). Currently, a general consensus does exist on the fact that the merging takes several orbits to occur and, in any case, when the merging process starts, \dot{M} rapidly increases, driving to the formation of an hot corona surrounded by a thick disk around the WD companion.

At contrast, Pakmor et al. (2010, 2011) suggested that the DD systems made by two CO WDs more massive than $\sim 0.9M_{\odot}$ and with mass ratio larger than 0.8 undergo a violent merging. Pakmor et al. (2012) computed the full evolution of a $1.1+0.9 M_{\odot}$ initial binary system, from the merging phase through a prompt thermonuclear explosion. Such a finding has been questioned by Dan et al. (2011) and Raskin et al. (2012), even if they show that a detonation occur for sure if the destroyed component has a large enough pure He buffer on the surface or it is an He WD.

Shen et al. (2012) and Schwab et al. (2012) analyze the long term evolution of the post-merging configuration and they claim that the disk formed during the merging rapidly disperses its angular momentum, thus evolving into an expanded, slowly rotating, almost spherical envelope. In this case off-center carbon ignition will occur either during the merging or when the expanded envelope relaxes and contracts thus producing an O-Ne-Mg core which eventually will collapse, if the total mass of the initial binary is larger than M_{Ch} . However, in this scenario the accretion on the central object is inhibited thus forcing the the disk-like configuration to dissipate its angular momentum. Therefore, the results by Shen et al. (2012) can not be used to exclude the formation of a keplerian disk and the consequent accretion at \dot{M}_{Edd} onto the survived CO WD.

The post-merging evolution of a CO WD plus a thick accretion disk has been analyzed first by Nomoto & Iben (1985) and Saio & Nomoto (1985, 1998) assuming $\dot{M} \sim \dot{M}_{\text{Edd}}$ and neglecting the effect of rotation. According to their results, C-burning is ignited off-center and it propagates in-

ward up to the center, producing a O-Ne-Mg WD which eventually could collapse into a neutron star (Isern et al. 1983; Hernanz et al. 1988). The effect of rotation in the evolution of merged CO WDs was included for the first time by Piersanti et al. (2003a). Basing on this systematic investigation of the thermal response of the accreting WD on the mass and angular momentum deposition, PGIT proposed an evolutionary model describing the evolution of the whole accretion process up to the C-ignition at the center in high degenerate physical conditions. PGIT show that, due to the continuous mass accretion at a very high rate and the deposition of angular momentum, the accreting WD experiences a Roche instability at the equator. As explained in Tornambé et al. (2004), in this situation matter can not be further deposited and the accretion process comes to a halt. The thermal energy excess in the accreted layers produced by the previous very fast accretion begins to be removed via inner thermal diffusion. Hence, the WD contracts and recedes from the critical rotation condition on the thermal timescale of the hot and expanded surface layers. As a consequence, matter and angular momentum can be deposited once again and the accreting WD reacts by expanding and adopting an overcritical configuration. This implies that accretion occurs not as a continuous process but as isolated episodes and, hence, the resulting “effective” accretion rate onto the WD decreases. We remark that the exact average value of \dot{M} is determined by the conditions that the angular velocity at the interface star/disk is close to the critical keplerian value. Since the process is driven by the thermal response of the WD to mass and angular momentum deposition, PGIT defines this accretion regime as “self-regulated”. Two major consequences arise: 1) the off-center of C-burning is avoided and 2) the total angular momentum of the WD continuously increases. As a matter of fact, the accreting object becomes a massive very fast rotator and it adopts a triaxial configuration (Jacobi ellipsoid). In this condition, gravitational waves can be emitted. The angular momentum loss stabilizes the accretion rate so that the WD increases its mass at an almost constant rate up and beyond the canonical M_{Ch} . Also in this case the star self-regulates the amount of matter which can be accreted, since the angular momentum losses depend on the ratio of rotational over the gravitational energy of the accreting WD (Friedman & Schutz 1975).

Saio & Nomoto (2004) generalized the work by PGIT, as differential rotation is accounted for, and according to their simulations off-center C-ignition occurs in any case. The difference in the final result is mainly determined by a different assumption on the accretion process. In particular, both the two groups find that, due to the deposition of matter and angular momentum, the accreting WD experience very soon the Roche instability. PGIT describe the following evolution by assuming that matter is accreted at an effective accretion rate smaller than the initial value and that the accreted matter carries angular momentum in any case. Saio & Nomoto (2004) assume that, when the surface rotational velocity is nearly critical, angular momentum can be transferred back from the WD to the disk via magnetic torque (Paczynski 1991; Popham & Narayan 1992), while \dot{M} maintains its initial high value. Since the rule of thumb is that high accretion rate drives to off-center C-ignition (valid also for rotating WDs) this is obtained very soon.

Yoon et al. (2007) followed the merging process of a $0.9+0.6 M_{\odot}$ CO WDs initial binaries with a SPH simulation and use the resulting final configuration as input for modeling the long thermal phase of mass accretion. Their approach is more refined than those in PGIT and Saio & Nomoto (2004) as they consider a central stellar-like object made by a compact, cold isothermal core rotating at slow rate surrounded by an hot extended envelope where angular velocity rapidly increase up to its breakup value. A centrifugal-supported disk provides the reservoir for matter deposition onto the inner object. In their computation Yoon et al. (2007) assume that, if the surface of the accreting core is rotating at a sub-keplerian angular velocity, angular momentum is deposited by the accreted matter, otherwise it is set to zero. Moreover, they allow the dissipation of angular momentum from the WD to the disk through all the accretion process. They finally obtain that off-center C-ignition is unavoidable for rapid accretion process, while a reduction of \dot{M} automatically drives to the onset of a thermonuclear runaway in the center once all the matter in the disk has been accreted onto the surviving stellar component. In this case rotation allows to obtain a spread in the total mass of the exploding object. As for the computations performed by Saio & Nomoto (2004), the results by Yoon et al. (2007) depend on the assumption that at the onset of the Roche instability angular momentum is no longer added but it is subtracted from the accretor.

Our evolutionary models have been computed with an updated version of the 1D hydrostatic lagrangian evolutionary code FRANEC, firstly described in Chieffi & Straniero (1989) and then revised in Chieffi, Limongi & Straniero (1998). The hydrostatic approximation adopted in the present work is suitable for our purposes, since we model the secular evolution of the accreting WD by assuming that matter flows from the newborn disk.

As in Piersanti et al. (2003a) and Piersanti et al. (2003b) we adopt the equation of state computed by Straniero (1988) and successive updates (Prada Moroni & Straniero 2002). We use the tables of radiative opacity provided OPAL group (Iglesias & Rogers 1996) for $T < 5 \times 10^8$ K, while at higher temperature we adopt the ones derived from the Los Alamos Opacity Library (Huebner et al. 1977). The contribution of the electron conduction to the total opacity is included according to the prescription by Potekhin et al. (1999).

The chemical composition of the surface layers of all the computed model is equal to $X_{12C}=0.506$ $X_{16O}=0.482$ and $X_{22Ne}=0.011$ while heavier elements are assumed to have solar abundances. This chemical pattern is representative of matter having experienced He-burning in a shell and is used as chemical composition of the accreted matter.

As discussed in Piersanti et al. (2003a), the effects of rotation are included into the stellar structure equations by adopting the approximation by Kippenhahn & Thomas (1970) for the centrifugal potential, *i.e.* by averaging over a sphere the radial component of the centrifugal force. The effective gravity in the hydrostatic equilibrium equation is computed as the product of the local gravity and the factor f , defined as the ratio of mean centrifugal force and the gravitational one per unit mass. In formula:

$$\frac{dP}{dr} = -\frac{GM}{r^2}\rho(1-f) \quad (1)$$

As in Piersanti et al. (2003a) we neglect the corrective factor in the expression for the radiative temperature gradient (but see the discussion in Endal & Sofia 1976). As discussed in Yoon & Langer (2004), the 1D approximation in the computation of the effective local gravity is accurate for angular velocities not exceeding $\sim 60\%$ of the local critical value. For larger value, the adopted numerical procedure underestimates the centrifugal force. The consequence of such a limitation is discussed in §3.

We assume that accreting WDs are rigid rotators, since they are fairly chemical homogeneous compact objects so that angular momentum redistribution could occur on a very short timescale as compared to the evolutionary timescale (Piersanti et al. 2003a; Maeder & Meynet 2000). Moreover, as discussed in Piro (2008), the occurrence of baroclinic instabilities and/or the shear growth determined by small magnetic fields determine a torque large enough to enforce rigid rotation in accreting WDs. Therefore, the time evolution of the angular velocity for accreting WDs is provided by the following equation:

$$\omega(t) = \frac{J_0 + J_{accr}}{I(t)} \quad (2)$$

where J_0 is the initial WD angular momentum after the merging process, J_{accr} is the amount of the angular momentum deposited by the accreted matter, and $I(t)$ is the momentum of inertia. For J_{accr} we adopt the following expression

$$J_{accr} = \Delta M \cdot \frac{2}{3} R_{WD}^2 \omega_{cr} \quad (3)$$

where ω_{cr} is the critical value of the angular velocity at the surface, R_{WD} the surface radius and ΔM the amount of matter accreted at each time step. The determination of the angular velocity value is coupled to the solution of the equations for the stellar structure at each time step in order to take into account the feedback of the changes in the radius coordinate onto the ω value and, hence, on the factor f .

If during the evolution the centrifugal force acting on a generic mass element of the star exceeds the local gravitational force (corresponding to the condition $f \geq 1$) the Roche instability occurs and the elements acquires a radial velocity larger than the escape velocity. Since ω_{cr} is a monotonically decreasing function of the radius and rigid rotation has been assumed, the Roche instability first occurs on the surface layer of the accreting WDs. Then, the amount of matter (and angular momentum) accreted at each time step is fixed by the condition that the star remain gravitationally bound ($f < 1$ at the surface).

The possibility that the equipotential surfaces could deform as the accreting WD spins up due to the continuous deposition of angular momentum can be checked by computing the quantity $\gamma = E_{rot}/E_{grav}$, where E_{rot} and E_{grav} are the total rotational and gravitational energy of the star, respectively. If such a quantity becomes larger than $\gamma_c \sim 0.1375$ (Friedman & Schutz 1975) GWR are emitted carrying away angular momentum from the star at a rate given by

$$\frac{dJ}{dt} = -\frac{J_*}{\tau_{GWR}} e^{-t/\tau_{gwr}} \quad (4)$$

where J_* is the actual total angular momentum of the star and τ_{GWR} , the characteristic timescale for the GWR emis-

sion, is computed according to Friedman & Schutz (1975) and Chandrasekhar (1970).

When all the matter available in the system has been transferred to the WD or when the WD itself approaches the Chandrasekhar mass limit for rigidly rotating objects, we assume that the evolution is driven by the angular momentum loss from the star (Piersanti et al. 2003b). In this case the efficiency of various physical mechanisms currently at work is described by a characteristic timescale τ and the corresponding amount of angular momentum subtracted at each time step is computed according to Eq. (4).

3 EVOLUTION TOWARD THE EXPLOSION

In the following we will refer to the evolutionary outcomes of the self-regulated accretion scenario for merged DD systems originally presented in PGIT. Following their prescriptions for the evolution of the merged object, we compute a number of additional models to better describe the broad spectrum of physical situations expected to occur in nature. In the present work we focus only on the behaviour of the accreting WD during the evolution to the explosion, not accounting for the contribution of the accretion disk to the observational features.

The evolution in the HR diagram along the accretion phase of a CO WD with initial mass $M_{WD} = 0.8M_{\odot}$ is reported in Fig. 1. The CO rich material flows directly from the disk formed by the disruption of a $0.7M_{\odot}$ CO companion during the merging phase.

We recall that during the pre-merging phase the two components interact tidally so that part of the rotational energy of the system is employed to maintain the synchronization of the orbits and to heat both the WDs. As a consequence, at the merging the two compact objects rotate very rapidly and, in addition, their temperature profiles are largely modified relative to those of the initial structures. This implies that just before the merging the two WDs evolve in the HR diagram along the cooling sequence toward larger surface luminosities and temperatures (dotted line in Fig. 1 up to point A for the more massive component). The evolution towards the merging is driven by the emission of gravitational wave radiation, which extracts angular momentum from the system, determining the spiral-in of the two components (Iben & Tutukov 1984) and giving rise to first detectable GWR signature (Nelemans, Yungelson & Portegies Zwart 2001, 2004; Yu & Jeffery 2010). Such an occurrence is labeled in Fig. 1 as *System GWR*.

The post-merging system is composed by the initially more massive component and by a disk formed by the disruption of the initially less massive CO WD. Lorén-Aguilar, Isern & García-Berro (2009) analyzed in detail the merging process by means of hydrodynamical computations. They find that, if the mass ratio of the WDs is not close to 1, the newborn disk is rather thin and very extended. Moreover, as already mentioned, off-center C-burning ignited at the WD-disk interface as soon as the merging starts, is rapidly quenched. Under these conditions, matter is expected to flow from the disk to the surviving CO WD depositing both angular momentum and energy. Lorén-Aguilar, Isern & García-Berro (2009) are not able to

determine the effective accretion rate from the disk to the WD, even if they tend to prefer a high value of \dot{M} because of the instabilities affecting the disk. In such a case, if no other physical mechanism is at work, accreted carbon would be ignited very soon in the accreted layers and C-burning should steadily propagate toward the center, producing an O-Ne-Mg WD, which eventually will collapse to a neutron star, avoiding a thermonuclear explosion. On the other hand, according to the DD rotating scenario the effective \dot{M} is regulated by the thermal and angular momentum content of the accreting WD. In particular, accretion occurs when the WD is in a condition to accept matter and it lasts for the time the physical properties of the accretor allows it to occur, as discussed in the following (see also the discussion in Isern, García-Berro & Loren-Aguilar 2012).

We distinguish four different phases in the evolution of the merged object:

(i) **constant \dot{M} phase:** initially matter flows from the disk to the WD at a very high rate ($\dot{M} \geq 10^{-5}M_{\odot}\text{yr}^{-1}$). Due to the large amount of thermal energy delivered by the accreted matter, the external layers of the accreting WD heat up, while the surface radius greatly increases as a result of both the local thermal excess and the rapid spinning up. Hence, both the surface luminosity and temperature increase (solid line in Fig. 1). When expansion becomes the leading parameter of the evolution, the external layers begin to cool and the surface luminosity decreases;

(ii) **first self-regulated accretion phase:** as the accreting WD spins up, due to the deposition of angular momentum by the accreted matter, and the external layers expand, the critical rotational velocity is attained for the first time (point B in Fig. 1). As a consequence, matter can no longer be accreted and mass transfer comes to a halt for a while. Thermal energy continues to flow from the surface layers toward the inner zones. The consequence of this new situation is that the WD contracts and recedes from the critical condition, so that accretion can resume again and proceed up to when the critical rotational velocity is attained once more. During this phase the accretion process is therefore driven by the thermal diffusion timescale of the accreting object. As a matter of fact, the rate at which matter is effectively deposited onto the WD reduces with time and, hence, also the surface luminosity decreases (dashed line in Fig. 1). In fact, the thermal transfer time scale becomes longer since the thermal gradient between the surface and the inner layers is reduced with time. This means that it becomes harder and harder for the star to recede from the critical condition.

(iii) **GWR-driven accretion phase:** should no other phenomenon occur, accretion would come to a definitive halt. But the continuous deposition of angular momentum by the accreted matter, increases the rotational energy until the latter exceeds a critical fraction of the gravitational energy (point C in Fig. 1). In this condition gravitational wave emission sets in and lasts for a long time. GWR allows the accreting WD to constantly recede from the critical condition, thus accreting matter (and momentum) at an almost constant accretion rate. This corresponds to a continuous decrease of the surface radius and to a corresponding heating of the surface layers via compression. Then, the surface luminosity increases once again (long-dashed line in Fig. 1). Later on, when a large part of the thermal en-

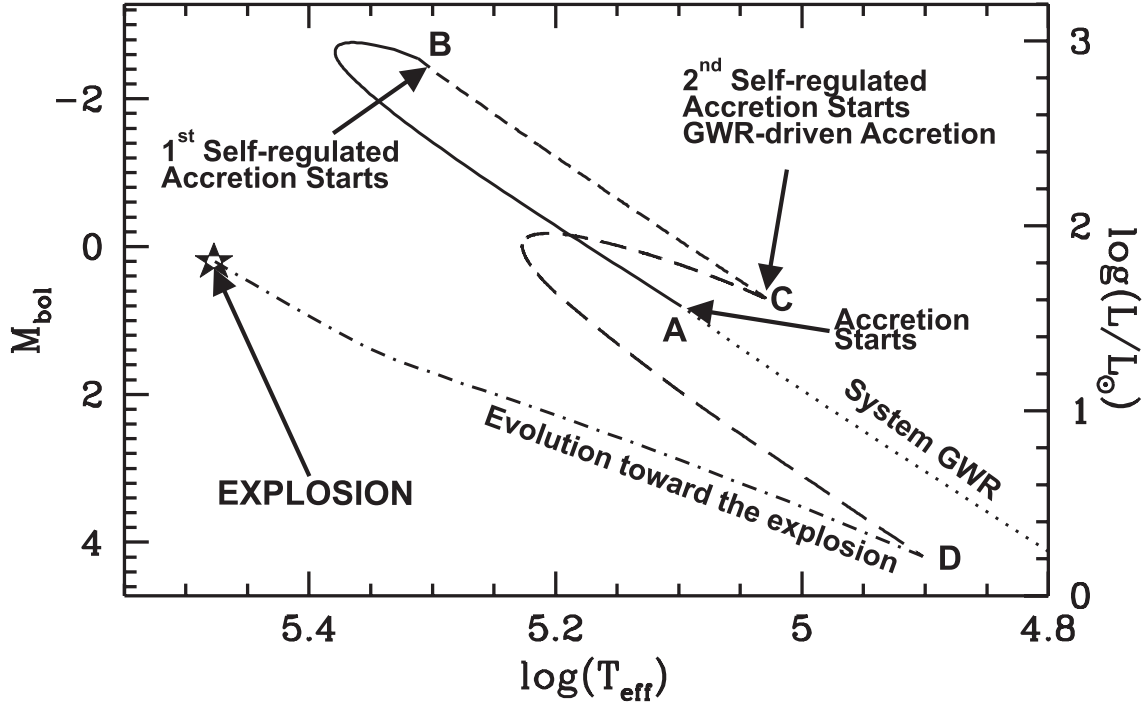


Figure 1. Evolution in the HR diagram of a CO WD with initial mass $M=0.8 M_{\odot}$ accreting CO-rich matter from a thick disk formed by the $0.7 M_{\odot}$ CO WD companion during the merging (see text for details).

ergy locally stored in the accreted layers is removed via inward thermal diffusion the surface luminosity decreases. When the accreting WD approaches M_{Ch} for rigidly rotating degenerate objects, the secular stability is attained once again and GWR emission ceases (point D in Fig. 1). Hence the accretion rate rapidly decreases and matter cannot be any longer accreted. During all this phase the accreting WD may deviate slightly from axisymmetry around the principal rotation axis. This implies that the WD acquires both a poloidal and an equatorial ellipticity, thus producing two “spectral line” in the emitted gravitational radiation. We consider only the gravitational emission related to the ellipticity in the equatorial plane, whose frequency is equal to the double of the spinning frequency of the WD (Zimmermann & Szedenits 1979). The amplitude of this signal is computed according to Shapiro & Teukolsky (1983) as:

$$h_0 = \frac{G^2 M_{WD}^2}{c^4 R_{WD}} \frac{1}{d} \quad (5)$$

where d is the distance from the source and M_{WD} and R_{WD} the actual value of mass and radius of the accreting object, respectively. The time evolution of the GWR characteristics are reported in Fig. 2 where we plot also the time evolution of the surface luminosity.

(iv) **Evolution toward the explosion:** the final part of the evolution is triggered by the loss of angular momentum from the accreted WD; this implies that the structure contracts homologously and heats up by compression up to the explosion. As a consequence, the surface luminosity increases (dot-dashed line in Fig. 1). During this phase, the WD reacts to the angular momentum loss by spinning up. This is clearly shown in Fig.3, where we report the evolu-

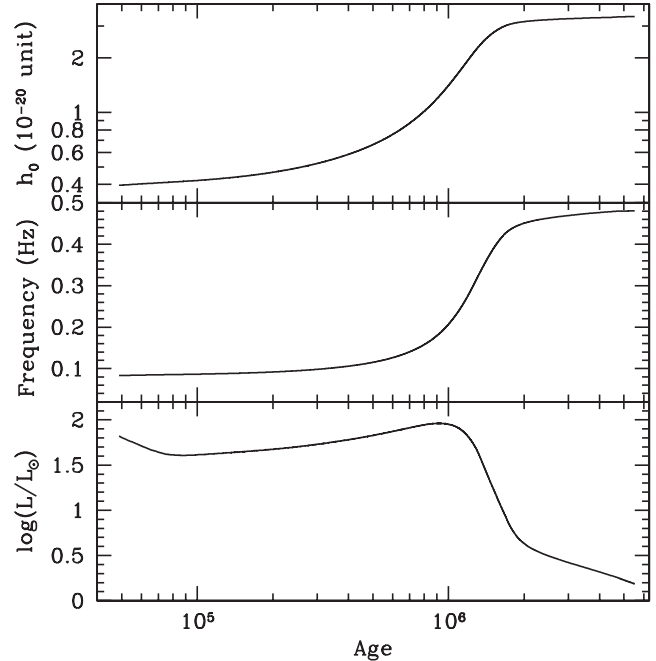


Figure 2. Some physical properties of the same model as in Fig. 1. *Upper panel:* time evolution of the GWR amplitude at a distance of $d=1$ kpc from the source. *Middle panel:* time evolution of the GWR frequency. *Lower panel:* time evolution of the surface luminosity of the accreting WD.

tion of the angular velocity as a function of time after the accretion halts and up to the C-ignition at the center. For the model with $\tau = 10^5$ yr the rotational velocity increases from 1.51 rad s^{-1} (point D in Fig. 1) to 3.19 rad s^{-1} (point

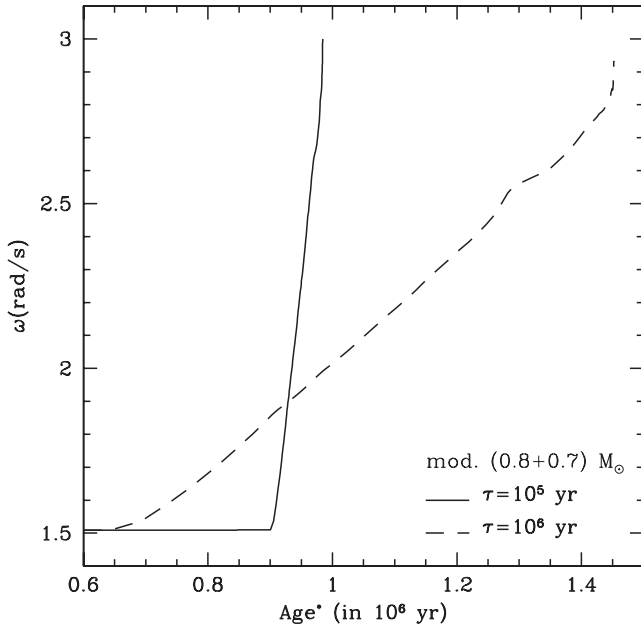


Figure 3. Time evolution of the angular velocity of the accreted WD during the last part of the evolution driving to the explosion for the model $(0.8+0.7)M_{\odot}$. The abscissa (Age^*) represents the time elapsed from the halt of the accretion process up to ignition of C-burning at the center. The two lines refer to model computed with different braking efficiencies, as labeled inside the figure (for more details see §3 and §4).

“Explosion” in the same figure). Such an occurrence can be easily explained by observing that the contraction triggered by the angular momentum loss produces the reduction of the momentum of inertia of the star and hence the increase of angular velocity due to the conservation of total angular momentum (Geroyannis & Papasotiriou 2000; Boshkayev et al. 2012). We note that Ilkov & Soker (2012) analyze in detail this evolutionary phase up to the explosion for a differentially rotating WD formed in the framework of the Core Degenerate scenario (Kashi & Soker 2011). They conclude that the emission of gravitational wave radiation in the r mode is inefficient at all to drive the merger remnant to the explosion and propose as effective braking mechanism the emission of magneto-dipole radiation. **In our models we fix the value of τ according to the analysis performed by PGIT, by assuming an intermediate efficiency of the physical processes driving the angular momentum losses. The angular momentum is subtracted from the WD according to Eq. (4).**

We note that the rotating DD scenario is the direct consequence of the self-consistent inclusion of rotational effects in the accretion process. The only free parameter in the model is the initial value of the accretion rate after the merging process, which affects just the duration of the constant \dot{M} and self-regulated accretion phases and the maximum attained luminosity, leaving unaltered the final result. This is clearly shown in Fig. 4, where we report the time evolution of the surface luminosity for models with the same initial WD mass and thermal structure as in PGIT, but with different values of \dot{M} for the post-merged configuration, as labeled inside the figure. In Tab. 1 we report for each model in Fig.

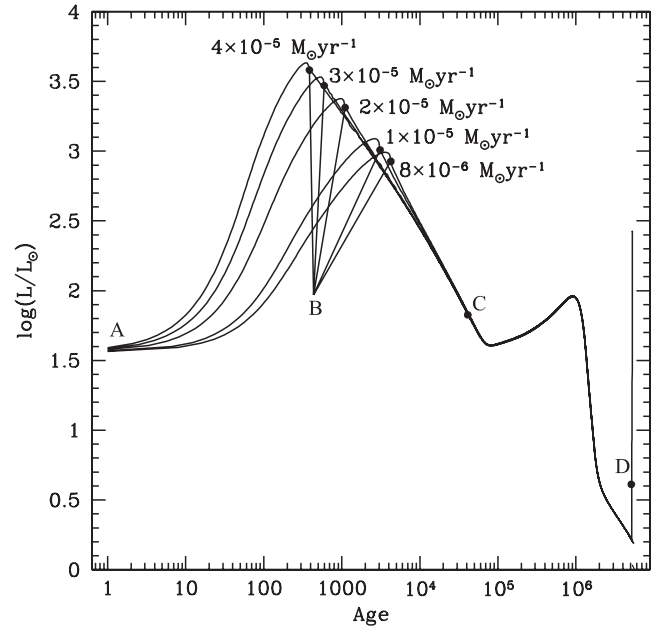


Figure 4. Time evolution of the surface luminosity of a CO WD with initial mass $0.8 M_{\odot}$ and different values of \dot{M} (as labeled) at the beginning of mass accretion process from the disk to the WD. The filled dots mark the onset of the various accretion regimes: A - constant \dot{M} ; B - self-regulated accretion phase; C - GWR-driven accretion phase; D - Final path to explosion. For more details see text.

4 the time duration of the four different evolutionary phases up to the explosion.

It is important to note also that the main features of the PGIT model (*i.e.* the self-regulation of the effective accretion rate and the emission of GWR) remain unaltered also when taking into account both the limitation of computing 1D models and the possible uncertainty in the amount of angular momentum effectively deposited after the onset of the critical rotation condition ($\omega_{WD} \simeq \omega_{cr}$). In particular, when considering that in 1D models the local effective gravity is overestimated in stellar layers with $f > 0.6$, it turns out that the corresponding surface radius of the accretor is underestimated. This implies that the WD attains sooner the critical condition, but such an occurrence does not affect the following evolution, which is driven by the thermal response of the accretor to mass and angular momentum deposition.

Similar considerations can be done also when assuming that a smaller amount of angular momentum is deposited by the accreted matter after the onset of the critical rotation condition. In fact, the angular momentum increases at a lower rate and the condition $\gamma \geq \gamma_c$ is attained later, so that the self-regulated accretion phase lasts for a longer time. However, when gravitational waves start to be emitted, the further evolution is driven by the GWR timescale and, hence, the average value of \dot{M} remains practically unaltered as well as the time up to end of the accretion process.

This scenario well describes also the evolution of differentially rotating CO WDs which accrete matter from a CO rich disk, as conjectured in Piersanti et al. (2009). In fact, the time evolution of the accretion rate is exactly the same, since it is determined by the same physical processes,

Table 1. Time duration of the various accretion phases experienced by a $0.8 M_{\odot}$ CO WD accreting CO rich matter as a consequence of a merging with its degenerate companion of $0.7 M_{\odot}$ as a function of different initial \dot{M} .

\dot{M} ($M_{\odot}\text{yr}^{-1}$)	ΔT_{AB} (yr)	ΔT_{BC} (yr)	ΔT_{CD} (yr)	ΔT_{DE} (yr)
8×10^{-6}	4281	38524	5119599	84257
1×10^{-5}	3096	40171	5205641	83863
2×10^{-5}	1104	41422	5212430	83308
3×10^{-5}	595	41700	5079911	89886
4×10^{-5}	385	41658	5457113	89856

AB: Evolutionary phase with $\dot{M}=\text{const.}$; *BC*: Self-regulated accretion phase; *CD*: GWR-driven accretion phase; *DE*: Evolution up to the explosion.

while the duration of the GWR-driven accretion phase can increase by a factor up to 2-3, depending on the total mass of the system at the merging time (from 1.4 up to $2.4 M_{\odot}$ as discussed in Piersanti et al. 2009). On the other hand, in differentially rotating structures, after the accretion comes to a halt due to the lack of matter in the disk, the evolution toward the explosion is triggered by the inner angular momentum redistribution via viscous shear, occurring on a timescale of the order of $10^5 \div 10^6$ yr.

It is important to note that the evolutionary path previously described is followed also by DD systems with total mass smaller than the standard non-rotating Chandrasekhar limit; in this case, when all the matter in the disk has been transferred to the surviving component, the following evolution does not lead to an explosion but to a cooling massive WD. In order to make more clear this point we present additional evolutionary sequences of merged DD systems with different total mass and mass of the primary component, namely DD systems made by a $(0.6+0.5) M_{\odot}$, $(0.7+0.6) M_{\odot}$, $(0.9+0.6) M_{\odot}$ and $(1.0+0.5) M_{\odot}$ CO WDs.

In our computations we follow the same prescriptions as in PGIT, but we adopt for the initial phase with constant \dot{M} the value of $4 \times 10^{-5} M_{\odot}\text{yr}^{-1}$. The results are summarized in Fig. 5, where we report as a function of the accreting WD mass the effective accretion rate (upper panel), the surface luminosity (middle panel) and the effective temperature (lower panel). The sudden drop of the curves in the three panels at $M=1.1$ and $M=1.3 M_{\odot}$ marks the end of the accretion process due to the exhaustion of the matter reservoir in the accretion disk for models $(0.6+0.5) M_{\odot}$ (solid line) and $(0.7+0.6) M_{\odot}$ (dotted line), respectively. Fig. 5 also discloses that the physical properties during the GWR-driven accretion phase are largely independent of the initial mass of the accreting WD. Moreover, since during this phase accreting WDs are rotating with angular velocity equal to the critical one, which depends only on the surface radius, it transpires that the amplitude and the frequency of the emitted gravitational radiation do not depend on the initial value of M_{WD} , but depend only on the actual value of the total mass.

In Tab. 2 we report the time duration of the accretion regimes experienced by these newly computed models. Since the $(0.6+0.5)$ and $(0.7+0.6) M_{\odot}$ models do not attain the physical conditions suitable to produce a SN Ia event as the final total mass of the accreting WDs is smaller than the standard non-rotating M_{Ch} , ΔT_{DE} can not be defined.

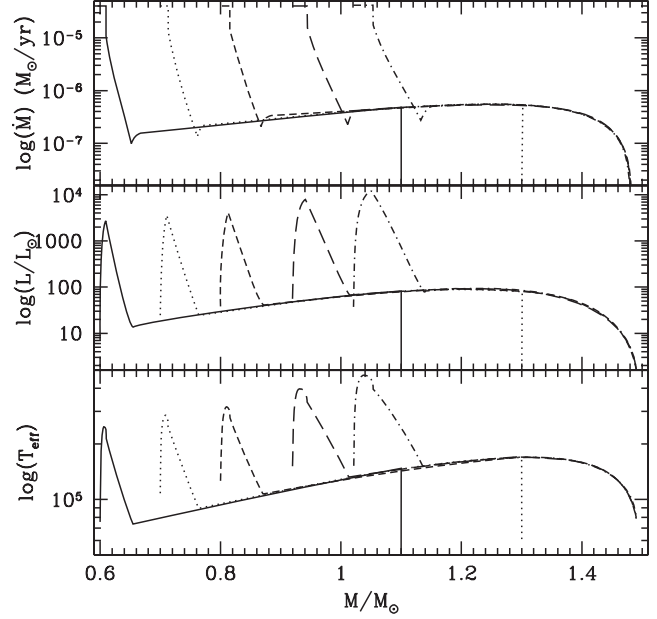


Figure 5. Evolution, as a function of the total mass of the accreting WDs, of the effective accretion rate (*upper panel*), of the surface luminosity (*middle panel*) and of the effective temperature (*lower panel*). The initial accretion rate for the post-merging objects has been fixed to $\dot{M} = 4 \times 10^{-5} M_{\odot}\text{yr}^{-1}$. Solid lines refer to the $(0.6+0.5) M_{\odot}$, dotted lines to the $(0.7+0.6) M_{\odot}$, dashed lines to the $(0.8+0.7) M_{\odot}$, long-dashed lines to the $(0.9+0.6) M_{\odot}$ and dot-dashed lines to the $(1.0+0.5) M_{\odot}$ models, respectively.

Table 2. Time duration of the various accretion regimes experienced by models with different total mass and mass of the accretor, by fixing the values of \dot{M} during the constant accretion rate phase at $4 \times 10^{-5} M_{\odot}\text{yr}^{-1}$. For the sake of completeness, we report also the data relative to the model $(0.8+0.7) M_{\odot}$.

Model	ΔT_{AB} (yr)	ΔT_{BC} (yr)	ΔT_{CD} (yr)	ΔT_{DE} (yr)
$(0.6+0.5)$	245	58960	1815793	-
$(0.7+0.6)$	318	52203	1513552	-
$(0.8+0.7)$	385	41658	5457113	89956
$(0.9+0.6)$	607	52105	5099653	84190
$(1.0+0.5)$	802	55865	4840686	84190

4 EXPECTED FREQUENCY OF PRE-EXPLODING SYSTEMS

In the following we estimate the expected number of pre-explosive systems in the Galaxy for each evolutionary phase after the formation of the accretion disk around the originally more massive CO WD and up to the explosion. We adopt the duration of various phases leading to the explosion of models initially accreting at $\dot{M} = 4 \times 10^{-5} M_{\odot}\text{yr}^{-1}$ as listed in Tab. 2. By an inspection of Tab. 1, it comes out that such a choice for the initial value of the accretion rate does not imply appreciable differences in the evolutionary timescales, except for the constant \dot{M} phase, which, in addition, is the shortest one. For the final approach to explosion we fix the braking timescale to $\tau_B = 10^5$ yr. Such an assumption may affect to some extent the estimated frequency, as discussed below in more detail. Finally, following

Table 3. Expected number of merged DD systems which will produce a SN Ia event in the Galaxy along various pre-explosion phases, as reported in the first column.

Evolutionary Phase	Merged DD systems
constant \dot{M}	2
Self-regulated accretion	208
GWR-driven accretion	27286
final path to explosion	421
Simmering	3

Bravo et al. (2011), we assume that the simmering phase, lasting from the crossing of the ignition curve up to the crossing of the dynamical curve, is equal to $\Delta T_{\text{simmer}} \simeq 530 \text{ yr}^1$. Since we focus our attention on the Galaxy, we assume an expected SN Ia rate of one event every 200 yrs (see, *e.g.*, Cappellaro, Evans & Turatto 1999; Li et al. 2011a).

In Tab. 3 we report the expected number of merged DD systems good candidates for SNe Ia progenitors for each evolutionary phase up to the explosion, the total being ~ 28000 . As already mentioned in the previous section, merged systems with initial total mass smaller than M_{Ch} experience the same evolution. Hence, they populate the initial parts of the same evolutionary phases, even if they end their life as massive CO WDs. On general grounds, it can be estimated that the number of merged DD systems less massive than M_{Ch} is only slightly larger (just ~ 1.5) than those with larger mass (Iben & Tutukov 1985; Tornambé 1989). The properties of this “SN manque” component deserve a more complex analysis via detailed population synthesis computations, which is far beyond the aim of the present work. So in the following we consider only those merged DD systems with total mass larger than M_{Ch} ; in this way we properly derive the properties of the binary population we are considering, even if we underestimate the number of objects contributing to each phase. **In our computation we assume that all the merged DD systems are uniformly distributed in the disk of the Galaxy.**

In Fig. 6 we report in the $\nu - h_0$ plane all the objects (27286) currently in the GWR-driven accretion phase. The sharp border at $\nu \sim 0.06 \text{ Hz}$ corresponds to systems with lower mass, close to the standard non rotating M_{Ch} , and which have just entered in the GWR-driven accretion regimes, while the other one at $\nu \sim 0.45 \text{ Hz}$ corresponds to systems which are attaining the limiting mass for the rigidly rotating degenerate objects, the very few objects (~ 50) with $\nu > 0.45 \text{ Hz}$ having already attained such a limit. The lower limit in h_0 represents the Galactic accreting systems furthest from the Earth. The clump of systems at high frequency ($\nu > 0.4 \text{ Hz}$) can be easily explained by noting that the last part of the GWR-driven accretion phase for massive DD systems is very long (see Fig. 2) since the rate

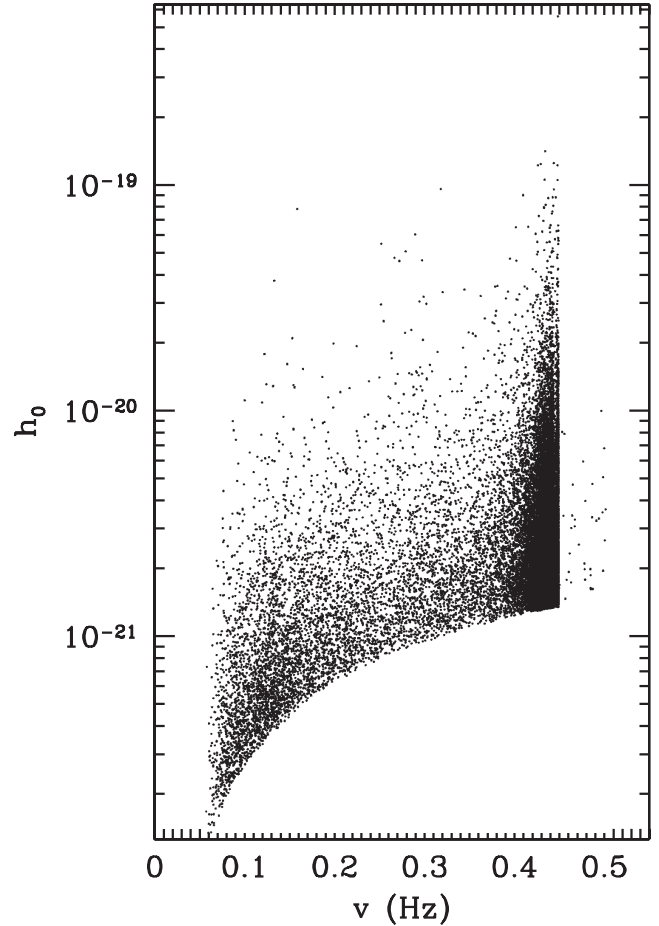


Figure 6. Distribution in the $\nu - h_0$ plane of all DD merged systems good candidates as SNe Ia progenitors.

at which matter is effectively accreted onto the WD rapidly decreases (see Fig. 5).

In Fig. 7 we report the expected number of objects experiencing the GWR-driven accretion phase as a function of the surface luminosity (left panel, solid line), of the GWR amplitude (middle panel) and of the corresponding frequency (right panel). As it can be noticed, only $\sim 25\%$ of these systems have a high luminosity (let say larger than $\log(L/L_{\odot}) = 1$), while louder GWR emitters ($h_0 \geq 3.2 \times 10^{-21}$) with larger frequency ($\nu \geq 0.44 \text{ Hz}$) corresponds to $\sim 30\%$ of the total number. It is important to remark that louder GWR emitters correspond to less luminous objects.

In Fig. 8 we plot the expected distribution in the apparent bolometric magnitude (m_{bol})-effective temperature plane of all the post-merged systems, good candidates for SNe Ia events. Systems currently experiencing the GWR-driven accretion phase have $T_{\text{eff}} \leq 178000 \text{ K}$ and apparent bolometric magnitude above the long-dashed line. Systems above this lines and with $126000 \leq T_{\text{eff}} \leq 400000 \text{ K}$ are experiencing the self-regulated accretion phase, while objects not currently accreting but evolving to the explosion are almost uniformly distributed in the bolometric magnitude range 14-20 and effective temperature range 90000 - 250000 K. The contribution of the latter component to the luminosity function of objects currently evolving toward an

¹ The evolutionary time elapsing from the onset of the thermonuclear runaway up to the moment when the nuclear timescale becomes comparable to the WD sound crossing time is usually addressed as “simmering”. During this phase, the combined action of convective mixing, carbon burning and e-captures largely modifies the chemical composition of the WD, thus determining to some extent the observational properties of the corresponding Supernova event.

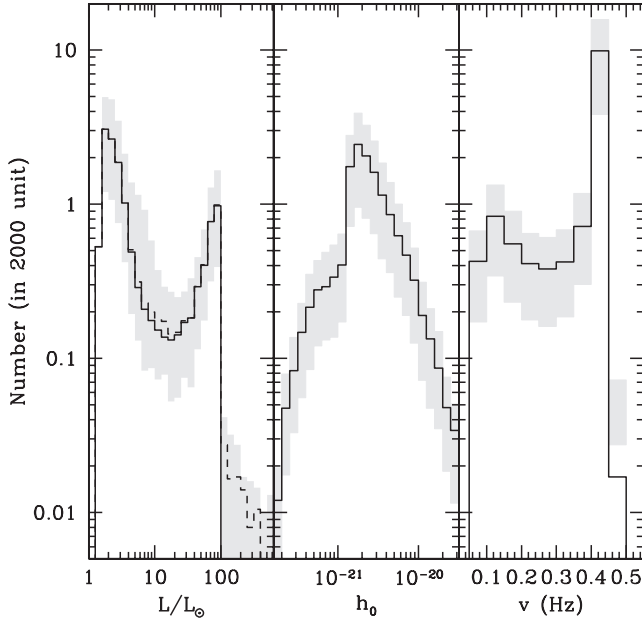


Figure 7. From left to right we plot the expected number of merged DD systems with $M_{tot} > M_{Ch}$ (normalized to 2000) experiencing the GWR-driven accretion phase as a function of the surface luminosity, amplitude of the emitted gravitational signal and corresponding frequency, respectively. The dashed line in the left panel refers to all the post merged system. The shaded region represents the uncertainty in the estimated numbers (for more details see text).

explosion of SN proportion is illustrated by the dashed line in the left panel of Fig. 7.

The main sources of uncertainty in the expected frequencies of merged DDs which will evolve into a SN Ia event are represented by the uncertainty in the SNe Ia rate of our Galaxy, which affects uniformly the number of systems in each evolutionary phase, and by the duration of the braking phase, which determines only the number of objects currently decaying to the ignition conditions. The former can vary in the range 0.2 - 1 Supernova per century, as derived by taking into account the uncertainties both in the observed rate and in the luminosity in the B band of the Galaxy. The latter mainly depends on the efficiency of angular momentum redistribution along the accreted WD and/or angular momentum loss by the star itself. In such a case, according to the analysis in PGIT, it can be derived that these processes occur on a time scale in the range $10^5 - 10^6$ yr. By combining together these uncertainties we derive that the number of merged DD systems good candidate as SNe Ia progenitors currently in the Galaxy may range from ~ 12000 to ~ 45000 , while the number of accreting objects emitting GWR varies in the range 11000 - 44000. The shaded region in each panel of Fig. 7 represents the maximum uncertainties for the estimated number of Galactic DD systems, which have already experienced a merging and with total mass larger than M_{Ch} .

5 DISCUSSION AND CONCLUSIONS

The overall analysis of the evolutionary path leading to a thermonuclear explosion clearly discloses that both the Sin-

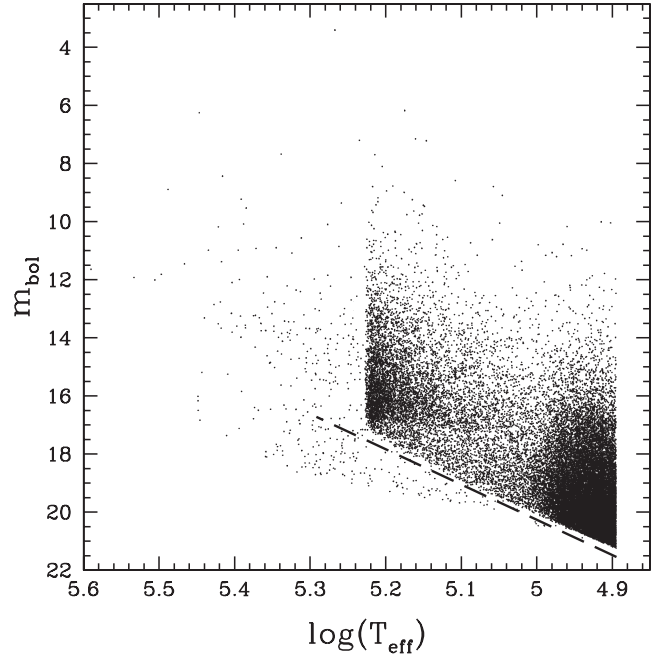


Figure 8. Distribution in the $T_{eff} - m_{bol}$ plane of all the Galactic post-merged DD systems with total mass larger than M_{Ch} . For more details see text.

gle Degenerate and Double Degenerate models for the progenitors of SNe Ia have severe problems. Up to now, the only possible solution to this impasse, at least for the DD scenario, is rotation, which represents, as first addressed by PGIT, the leading parameter regulating the accretion process. When rotation is accounted for, some important implications directly follow. First of all, the accreting WD can largely exceed the Chandrasekhar mass limit, the final value depending on the initial mass of the original DD system. This determines very easily a spread in the mass of the exploding objects, in the range 1.4 - 2.4 M_{\odot} . **If it is assumed that more massive progenitors produce larger amount of ^{56}Ni during the explosion, rotation could explain the differences in the observed magnitude at the maximum epoch in light curves of “normal SNe Ia” as well as the rare, very bright events, like SN 2003fg (Howell et al. 2006), SN 2007if (Scalzo et al. 2010) and SN 2009dc (Silverman et al. 2011; Taubenberger et al. 2011).** The second important consequence is that the explosion does not occur soon after all the matter in the disk has been accreted onto the WD, as rotation keeps the structure overstable. The thermonuclear runaway can occur only when, owing to the redistribution or loss of angular momentum, a strong compression of the whole structure occurs, triggering the explosive C-burning at the center. This corresponds to a radical change in our way of looking at thermonuclear Supernovae. In fact, the accreting WD does not attain a critical mass, but the value of the critical mass decreases up to the actual mass of the WD, thus determining the explosion. As a final consequence, it follows that it is practically impossible to find any trace of the progenitors of nearby recent SNe Ia in archival frames, as the explosion occurs several million years after the accretion has halted. The previous considerations

directly emerge by including rotation self-consistently in the modeling of SNe Ia progenitors and are valid for any kind of accreting scenario (*e.g.* for the SD scenario see Hachisu et al. 2012).

For this reason, according to the prescriptions in PGIT, we computed the evolution of merged DD systems by including the effect of rotation as the regulator of the accretion process. Several models with different initial parameters have been evolved from the heating regime, just before the merging of the two components, up to few seconds before the explosion, when a large convective core has already developed in the accreting WD and the hydrostatic equilibrium assumption is no longer valid.

We have demonstrated that the only free parameter in rotating DD models, the initial value of \dot{M} , does not affect the following evolution, regulated by well established physical properties and free of any further assumption. We showed that the accreting WD experiences three different accretion regimes, and we explained in detail their corresponding evolutionary properties. We also analyzed the gravitational signal emitted during the third accretion regime.

According to our results, the evolutionary properties of accreting WDs (luminosity, effective temperature, gravitational signal) depend only on the actual value of the total mass, but not on the initial parameters of the system or on the previous accretion history.

Using the computed models, we provide for the Galaxy an estimate of the expected number of merged DDs good candidates for SNe Ia progenitors currently emitting GWR and the properties of the gravitational signal in the $\nu - h_0$ parameter space as it should be observable from the Earth. We also provide the surface properties (apparent bolometric magnitude and effective temperature) of the accreting WDs.

The gravitational signal produced by these systems is largely below the sensitivity curve of the current generation of space born interferometers. For example, the LISA apparatus will be able to detect with a $S/N=1$ only very few events (2-3), corresponding to objects with total mass larger than the canonical M_{Ch} (*i.e.* with $\nu \geq 0.4$) and located inside 60 pc from the Earth. However, this could represent an unambiguous confirmation of the pivotal role played by rotation in the evolution of merged DD systems, as well as a clear indication that a part of the type Ia events arises from DD systems.

On the other hand, the next generation of space born interferometers, such as eLISA (evolved LISA: Laser Interferometer Space Antenna, Amaro-Seoane et al. 2012a,b) and DECIGO (Deci-Hertz Interferometer Gravitational-wave Observer, Hideaki et al. 2006), will be able to detect the whole range of frequencies and amplitudes shown in Fig. 6, thus providing a deeper insight into SNe Ia. As a matter of fact, it will be possible to get information on the actual spectrum of accreting WDs masses, thus shedding light on the efficiency of angular momentum transport in degenerate stars (differential *vs* rigid rotation). Moreover, the exact number counts of events as a function of the observed frequency and signal amplitude will allow one to determine if DD systems are the only progenitors of SNe Ia or if some additional contribution comes from different progenitor systems.

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